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Design Similarity Measures for Process Planning and Design Evaluation

by Jeffrey W. Herrmann, Gurdip Singh

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Design Similarity Measures for Process Planning and Design Evaluation

Jeffrey W. Herrmann
Gurdip Singh

Department of Mechanical Engineering and
Institute for Systems Research
University of Maryland
College Park, Maryland 20742
(301) 405-5433
(301) 314-9477 FAX
jwh2@eng.umd.edu

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Abstract

Design engineers and process planners need to search for similar designs. Design engineers use similar designs to estimate a new design's manufacturability. Like process planners, who need to generate process plans before production begins, design engineers can use an existing, similar design's process plan to create a new process plan. Then, they can evaluate the new design. Variant process planning, a common process planning approach, uses a design similarity measure to identify the most similar design and retrieve a useful process plan. However, standard design similarity measures do not explicitly consider the production process. This paper presents an approach for developing a new class of plan-based design similarity measures. Such a measure explicitly exploits process plan similarity and thus improves the variant process planning approach. An example illustrates the approach and compares the new measure and a traditional group technology code-based approach.

1. Introduction

Design engineers and process planners need to search for similar designs. Manufacturers, engineers, and researchers have understood for many years that designers (or product development teams) need to evaluate a new product design and gauge its manufacturability. This design evaluation helps designers identify potential manufacturing problems, redesign the product, and avoid unnecesary design iterations. There now exist a variety of manufacturability guidelines (see, for example, Bakerjian, 1982; Bolz, 1949; Bralla, 1986; Pahl & Beitz, 1984; Trucks, 1987; General Electric, 1960). Researchers have developed various approaches for evaluating designs, including direct (rule-based) and indirect (plan-based) methods. The more common direct approach inspects the design parameters and appraise the design's manufacturability by consulting rules that identify those design characteristics that improve or degrade the manufacturability (see, for example, Ishii, 1993; Jakiela & Papalambros, 1989). However, indirect approaches generate a process plan and then evaluate the cost and time associated the plan's component operations (see, for example, Hayes *et al.*, 1989, 1994; Hsu *et al.*, 1993; Minis *et al.*, 1996; Gupta, 1997). This plan-based approach requires the ability to generate a process plan. In addition to these two approaches, a designer can use an existing, similar design's manufacturability to estimate the new design's manufacturability (Candadai *et al.*, 1996).

Of course, because a process plan is a key piece of manufacturing information (as Section 2.1 discusses), generating the process plan has always been an important, though sometimes difficult and tedious, task in the product life cycle. Process planning itself has attracted considerable attention (see, for example, Halevi & Weill, 1995; Chang & Wysk, 1985), and researchers have developed various approaches for computer-aided process planning. Variant process planning has met the most success to date.

Truly effective variant process planning requires the ability to retrieve a process plan that is useful for the new plan. Since the retrieved process plan corresponds to the most similar design that the search finds, it is clear that the design similarity measure affects the variant process planning approach. However, existing (plan-independent) design similarity measures do not consider explicitly the process plan attributes. This may lead to instances when similar designs do not have similar process plans. And since the process plan clearly affects manufacturability, plan-independent design similarity measures may lead to instances when similar designs do not have similar manufacturability.

Variant process planning assumes that similar designs have similar process plans. To guarantee this assumption, a design similarity measure should have the following characteristics:

1. The design similarity measure should reflect the similarity between process plans. Thus, designs that are similar will indeed have similar process plans.

2. The design similiarity measure should precisely and consistently classify designs so that the search can identify the most similar designs (with the most useful process plans).

This paper presents an approach for developing a new class of plan-based design similarity measures. Such a measure explicitly exploits process plan similarity and thus improves the variant process planning approach. The measure exploits knowledge that describes the correlation between process plan attributes and design attributes. Because each manufacturing enterprise is unique, no single design similarity measure is a universally appropriate function. The design similarity measure must reflect the local manufacturing characteristics and priorities. Thus, the paper presents a three-step approach for using that knowledge to create a plan-based design similarity measure. An example illustrates the approach and compares the new measure and a traditional group technology code-based approach.

The remainder of this paper is organized as follows: Section 2 reviews related work on process planning and design similarity measures. Section 3 describes the plan-based design similarity approach. Section 4 presents the example. Section 5 concludes the paper.

2. Related Work

This section reviews previous work on process planning and design similarity measures.

2.1. Process planning

A process plan describes the steps necessary to manufacture a product. It specifies the type and sequence of the manufacturing operations that operators must perform to transform the components and raw materials into a set of parts. Some form of the process plan is used by designers, production planners, and manufacturing operators. A process plan may specify, for each step, the particular machine that will perform the step and the relevant process parameters that regulate the process. For instance, the process plan may specify the speed required to perform a drilling operation.

The earliest examples of process plans are operations sheets for sewing machine manufacture (Hounshell, 1984). Brown & Sharpe, a Rhode Island manufacturing company, used these sheets to list the operations and identify, for each operation, the necessary tools, jigs, fixtures, and gauges.

When done manually, process planning is a subjective and time-consuming procedure, and it requires extensive manufacturing knowledge. An experienced engineer or machinist must examine a part drawing and construct a process plan. The process planner must know or be able to find information about the manufacturing capabilities, tooling, materials, costs, and machine availability. In addition, the process planner must carefully document the plan using standard notation and forms.

Computer-aided process planning (CAPP) software systems automate many functions, which reduces the chance of error, and the process planner can work more quickly. Variant process planning systems have successfully exploited the assumption that similar designs have similar process plans. Thus, the most similar design will have the most useful plan. (A useful plan is one that requires few changes.) The CAPP software searches a set of existing designs, uses a design similarity measure to compare each existing design and the new design, identifies the most

similar existing design, and retrieves the corresponding process plan. (Some variant process planners find the most similar product family and retrieve that family's standard plan.) Then, the process planner modifies the process plan, changing the details so that the plan is appropriate for the new design. The new plan is therefore a variant of the old plan.

The earliest CAPP software systems employed the variant process planning technique. Several variant systems are commercially available today, and they currently support almost all practical implementations of CAPP. For more information, see, for example, Alting and Zhang (1989), Chang and Wysk (1985), and Bedworth *et al.* (1991). A typical variant process planning approach involves the following three steps:

1. The process engineer uses a group technology (GT) coding scheme to map a proposed design D into an alphanumeric code. As discussed below, GT codes are a popular design classification scheme.

2. This code is then used as an index into a database to retrieve a process plan P_O for the design D_O most similar to D (or for the family F_O that includes D or is most similar to D).

3. The planner then modifies the process plan P_O manually to produce a plan P for the design D.

Variant process planning is a popular technique:

1. Because the planner only modifies the retrieved plan, variant process planning reduces the total time that the planner requires to generate a complete process plan for the new design.

2. The planner has more time to generate and evaluate alternate process plans that reflect those design features that differ from the existing design.

3. This approach has been successfully implemented in several practical CAPP systems.

2.2. Design Similarity Measures

The most common design similarity measures are those associated with group technology and variant process planning. Other approaches include geometric similarity and neural net classifiers.

Group Technology. Mitrofanov (1966) first formally described group technology (GT) as a method that improves manufacturing efficiency by classifying similar products into families. Two formal methods of classifying designs for group technology are Production Flow Analysis (PFA), described by Burbidge (1989), and parts coding and classification analysis (PCA). PFA uses routing information to classify products into families, while PCA uses design information to derive GT codes.

A GT code is a sequence of numbers. Each position in the code represents some product attribute: thickness or the presence of holes, for example. Each possible value represents a set of values for that attribute. Different GT coding schemes have different attributes. Given a product

design and a specific coding scheme, the coding rules calculate what each attribute's value should be, and that yields a GT code for that product. Researchers have developed many GT coding schemes. Typical schemes include DCLASS (Computer Aided Manufacturing Laboratory, 1979), MICLASS (Houtzeel and Schilperoort, 1976), and OPITZ (Opitz, 1970). Also see, for example, Chang and Wysk (1985) and Bedworth *et al.* (1991). GT codes have many applications, including cellular manufacturing system design, materials management, tool management, process planning, and product standardization (Snead, 1989). Candadai *et al.* (1996) describe an application for design evaluation and partner selection.

The PFA approach examines the product routings and groups products that have similar routings. Usually, one can use clustering algorithms such as the rank order cluster algorithm (King, 1980) or mathematical formulations (Kusiak, 1987) to identify similar routings and classify products into families.

Variant process planning requires some way to represent the products that each family contains. If each product has been coded, the part family matrix (Chang and Wysk, 1985) describes, for each GT code position, all possible values that members of that family have. Thus, a new design belongs to a particular family if the GT code for the new design has, in each position, a value that exists in that family's part family matrix. That family's standard process plan becomes the new design's process plan.

PFA uses a rational approach to form families whose designs have similar routings. The subsequent search uses a GT code to classify a new design and then asserts that the GT code similarity implies that the new design should have a similar process plan. However, the GT code may not correspond to the process plan. Although the GT code captures some information that impacts manufacturing, the code does not explicitly describe the process plan. Thus, GT codes may be convenient for classification, but their use in this approach is inconsistent.

The PCA approach uses the GT codes to classify products into families. Offodile (1991) describes one such approach. The approach uses a similarity measure to evaluate each pair of products and calculate their similarity. This measure uses each product's GT code and averages the code digits' similarity. (Section 4's example illustrates this calculation.) A single linkage clustering algorithm then groups the products into families at different similarity thresholds. Each family has a part family matrix and a standard process plan. As before, a new design belongs to a particular family if the GT code for the new design has, in each position, a value that exists in that family's part family matrix. That family's standard process plan becomes the new design's process plan. Although Offodile's approach simply averages the absolute digit differences, Iyer and Nagi (1994) describe a more flexible GT code-based search.

The PCA design classification approach is consistent because the search uses the same criteria that the part family grouping does. Again, however, a design's GT code may not correspond to its process plan. It is not clear that the family's standard process plan would be a useful process plan for the new design Thus, this may be an inappropriate variant process planning approach.

Geometric Approaches. Many modern CAD/CAM systems use constructive or boundary models to represent solids. Thus, one can classify designs by using the geometry that the CAD models represent. Elinson, Nau, and Regli (1997) describe such approaches in detail.

Many solid models use Constructive Solid Geometry (CSG) trees as a basic representational scheme. Using CSG trees to classify designs seems natural because the component volumes may be the volumes that machining operations remove. However, the approach has two drawbacks. First, a design may have more than one CSG representation. Second, though similar, the CSG primitives do not always correspond to the manufacturing features; when they do not, the CSG tree does not describe the information that a plan-based design similarity measure needs.

Sun *et al*. (1996) have described a similarity measure for solids. This measure evaluates properties of their boundary representations. This is an interesting, new measure of “relaxed” geometric similarity. However, it has several difficulties that must be overcome before it can be useful as a classification scheme for manufacturing. First, the similarity measure can compare only polyhedral objects. Thus, the approach must facet (approximate with planes) a design that has cylindrical or sculpted faces. It is unclear how this approximation will affect the design similarity measure. The second difficulty is that the current measure addresses no manufacturing considerations such as approachability, operation interference, or fixturing. It is unclear if the design similarity measure can include these considerations.

Neural Nets. One promising approach (Leung, Hines, and Raja, 1994) exploits the strengths of the Artificial Neural Net (ANN) technique to associate a product's attributes with its process plan attributes. This approach does not use an explicit design similarity measure but implicitly maps the product attributes to the associated process plan attributes. However, the resulting process planning systems have yielded inconsistent results since the search’s success depends upon the ANN technique and the sample data used to train the net.

Other design classification approaches use neural nets to solve the form recognition problem (Wu and Jen, 1996). However, such approaches resemble the geometric approaches and share the same drawbacks.

Discussion. After appraising the existing design classification approaches, one can see that planners need a design similarity measure that identifies designs with similar process plans. Such a design similarity measure should have the following characteristics:

1. The design similarity measure should be plan-based. The design similarity measure should correspond to the process plan design similarity measure. In fact, two designs should be similar if and only if their process plans are similar. This will justify the variant process planning approach.

2. The design similarity measure must convey information to the process planner unambiguously:

- The design similarity measure must be precise. Given the similarity between two designs, the process planner should know precisely which attributes of the two process plans are similar and how similar they are.

- The design classification and search should be consistent. If the similarity between one pair of designs equals the similarity between another pair of designs, then the same (or an equivalently important) set of process plan attributes should be similar in both pairs of process plans.

3. The Plan-based Design Similarity Approach

This section describes a three-step approach for developing a plan-based design similarity measure. The measure will have the previously described desired characteristics. The measure calculates the similarity of two designs. The approach includes a process plan similarity measure and mapping functions that describe the correlation of the design attributes and the process plan attributes. These functions will incorporate local manufacturing characteristics and priorities.

Conceptual framework. A plan-based design similarity measure explicitly implements the idea that two designs should be similar if and only if their process plans are similar. Ideally, the similarity between two designs should equal their process plan similarity. In variant process planning, of course, the new design does not have a process plan. However, within a given manufacturing enterprise, it should be possible to determine (at least approximately) how the design attributes impact the important process plan attributes. Thus, the process plan similarity measure (a function of the process plan attributes) can be a function of the design attributes, and this yields the design similarity measure.

Consider the following hypothetical example. A car buyer wants to estimate a new car’s actual fuel efficiency (as opposed to the number that the dealer advertises). The buyer knows a lot about the new car and knows a lot about other existing cars and their actual fuel efficiency in this area. So the buyer thinks that the new car’s fuel efficiency will approach the fuel efficiency of similar cars. For this purpose, the buyer ignores a car’s color and the stereo (which do not impact the fuel efficiency) and instead considers a car’s weight (which does). The car whose weight most closely approaches the new car’s weight will provide the best estimate for the new car’s fuel efficiency.

In this case, the fuel efficiency similarity measure is the difference of two car’s fuel efficiencies. The buyer correlates weight and fuel efficiency, so the car similarity measure is the difference of two car’s weights. They buyer can use this measure to identify the most similar car and estimate the new car’s fuel efficiency. Of course, the buyer might find a better estimate by also considering the car’s engine displacement and whether or not it has air conditioning, since those attributes can also affect fuel efficiency. Also, note that the mapping function does not itself estimate the fuel efficiency; instead, it helps identify cars that may have similar fuel efficiency.

Limitations. This design similarity approach does not consider alternate process plans. If designs have alternate process plans, it may be more difficult to define mapping functions.

This approach does not require any particular process plan or design specification. The process planner can select and define any type or number of attributes that reflect local manufacturing characteristics and priorities. The process planner can specify any appropriate process plan similarity measure. This measure should be a consistent, precise function of selected process plan attributes.

However, the approach does require the planner to correlate design attributes and process plan attributes and to define mapping functions that describe these correlations. These functions can take any form and may approximate the correlations. They are not rules that completely construct a process plan. Instead, they describe how the selected design attributes affect the selected process plan attributes.

Step 1

The planner defines f, the process plan similarity measure, and selects the relevant process plan attributes.

$P_1, P_2, ..., P_n$ are process plans corresponding to designs $D_1, D_2, ..., D_n$, respectively.

$A_{1p}, A_{2p}, ..., A_{kp}$ are the process plan attribute values corresponding to the process plan P_p.

$P_p \equiv (A_{1p}, A_{2p}, ..., A_{kp})$ is the process plan attribute vector.

$f(P_i, P_j)$ is the similarity between process plan P_i and process plan P_j, which are the process plans for designs D_i and D_j.

$$f(P_i, P_j) = f\{(A_{1i}, A_{2i}, ..., A_{ki}), (A_{1j}, A_{2j}, ..., A_{kj})\}$$

Note that f should be a function of the identified process plan attributes.

Step 2

The planner select design attributes and defines, for each process plan attribute $i = 1, ..., k$, a mapping function g_i that describes the correlation between the design attributes and the process plan attributes.

$X_{1p}, X_{2p}, ..., X_{np}$ are the design attribute values corresponding to the design D_p.

$D_p \equiv (X_{1p}, X_{2p}, ..., X_{np})$ is the design attribute vector.

$g_i(X_{1p}, X_{2p}, ..., X_{np}) = g_i(D_p)$ is the mapping function for process plan attribute i.
Ideally, $A_{ip} = g_i(X_{1p}, X_{2p}, ..., X_{np}) = g_i(D_p)$.

$g(D_p) \equiv (g_1(D_p), g_2(D_p), ..., g_k(D_p))$ is the vector function that includes every mapping function.

Step 3

The planner defines h, the plan-based design similarity measure. $h(D_i, D_j)$ is the similarity between designs D_i and D_j.

$$h(D_i, D_j) = f(g(D_i), g(D_j))$$

Thus, $h(D_i, D_j) = f\{(g_1(D_i), g_2(D_i), ..., g_k(D_i)), (g_1(D_j), g_2(D_j), ..., g_k(D_j))\}$. The plan-based design similarity measure is a function of the design attributes, but it exploits the process plan similarity measure.

4. Example

This section illustrates the approach by developing a plan-based design similarity measure for a sheet metal shop and five synthetic designs. Each design is a sheet metal box similar to that shown in Figure 1. Designs D_3, D_4, and D_5 do not have the twelve top holes. In addition, Design D_3 does not have the five bottom holes. Table 1 lists the critical design information. Table 2 lists each design's process plan.

A typical process plan has the following operations: punching, forming, welding, grinding, drilling, and assembly. One punch press punches all parts. Two press brakes are available for forming. The first (Brake 6) can bend parts with bends no larger than six feet; the second (Brake 10) can bend parts with bends no larger than ten feet. (This example assumes that no bends are greater than ten feet.) Two welding workcenters are available. The first (Welding 1) performs spot welding; the second (Welding 2) performs smooth corner arc welds and grinds the part after welding to remove slag. (For the sake of simplicity, this example assumes that no designs have both type of welds.) One drill press drills the holes that cannot be punched. The assembly area assembles any parts that have anchors for screws.

The following subsections describe each step for developing a plan-based design similarity measure.

Step 1

P_1, P_2, P_3, P_4, P_5 are process plans corresponding to designs D_1, D_2, D_3, D_4, D_5.

$A_{1p}, A_{2p}, A_{3p}, A_{4p}$ are the process plan attribute values corresponding to the process plan P_p. Each attribute describes an optional operation in P_p.

$A_{1p} = 1$ if the process plan P_p includes a forming operation at Brake 6; $A_{1p} = 2$ if the process plan P_p includes a forming operation at Brake 10; otherwise $A_{1p} = 0$.

$A_{2p} = 1$ if the process plan P_p includes a spot welding operation at Welding 1; $A_{2p} = 2$ if the process plan P_p includes a smooth corner arc welding operation and grinding at Welding 2; otherwise $A_{2p} = 0$.

$A_{3p} = 1$ if the process plan P_p includes a drilling operation; otherwise $A_{3p} = 0$.

$A_{4p} = 1$ if the process plan P_p includes an assembly operation; otherwise $A_{4p} = 0$.

$P_p \equiv (A_{1p}, A_{2p}, A_{3p}, A_{4p})$ is the process plan attribute vector.

$f(P_i, P_j)$ is the similarity between process plan P_i and process plan P_j, the process plans for designs D_i and D_j.

$$f(P_i, P_j) = f\{(A_{1i}, A_{2i}, A_{3i}, A_{4i}), (A_{1j}, A_{2j}, A_{3j}, A_{4j})\}$$

Specifically, $f(P_i, P_j) = e_1 + e_2 + e_3 + e_4$. For each $k = 1, 2, 3, 4$, $e_k = 1$ if $A_{ki} = A_{kj}$ and 0 otherwise. Thus, $f(P_i, P_j)$ measures how many optional operations the two process plans have in common.

For this measure, if $f(P_i, P_j) > f(P_i, P_k)$, then P_i is more similar to P_j than it is to P_k.

Step 2

$X_{1p}, X_{2p}, X_{3p}, X_{4p}, X_{5p}$ are the design attributes corresponding to the design D_p.

X_{1p} equals the length (in inches) of the longest bent edge that design D_p has. If D_p has no bent edges, then $X_{1p} = 0$.

$X_{2p} = 1$ if the design D_p has any spot welds. $X_{2p} = 2$ if design D_p has any smooth corner arc welds. If design D_p has no welds, then $X_{2p} = 0$.

X_{3p} equals the minimum distance between a hole and a bent edge in design D_p. If D_p has no holes or D_p has no bent edges, then $X_{3p} = 0$.

X_{4p} equals the sheet metal thickness in inches.

$X_{5p} = 1$ if design D_p has any anchors for screws. Otherwise $X_{4p} = 0$.

$D_p \equiv (X_{1p}, X_{2p}, X_{3p}, X_{4p}, X_{5p})$ is the design attribute vector.

Now, consider the mapping functions. The first mapping function describes how the design attributes correlate to the first process plan attribute, A_{1p}, the type of forming operation. Clearly, a design's maximum bent edge length affects the forming operation. Specifically, if this maximum is greater than six feet, then Brake 10 must perform the forming operation. Otherwise, if the design has any bent edges, Brake 6 can perform the forming operation.

$g_1(D_p) = 0$ if $X_{1p} = 0$.
$g_1(D_p) = 1$ if $0 < X_{1p} \leq 72$.
$g_1(D_p) = 2$ if $X_{1p} > 72$.

The second mapping function describes how the design attributes correlate to the second process plan attribute, A_{2p}, the type of welding operation. The type of welding operation depends upon the welds that the design has. If the design has spot welds ($X_{2p} = 1$), then the process plan should include the spot welding operation ($A_{2p} = 1$). The same holds for smooth corner arc welds.

$g_2(D_p) = X_{2p}$.

The third mapping function describes how the design attributes correlate to the third process plan attribute, A_{3p}, the drilling operation. The process plan should include a drilling operation if the design has holes that are too close to a bent edge. The bending process would distort such holes. In this example, the minimum feasible distance between a punched hole and a bent edge is twice the sheet metal thickness (Radhakrishnan *et al.*, 1996, describe other feasibility rules). Recall that X_{3p} is the minimum distance between a hole and a bent edge in design D_p. X_{4p} is the sheet metal thickness of design D_p.

$g_3(D_p) = 0$ if $X_{3p} = 0$. (There exist no holes or no bends, so drilling is not required.)
$g_3(D_p) = 1$ if $0 < X_{3p} < 2 X_{4p}$. (A hole and a bend are too close, so drilling is required.)
$g_3(D_p) = 0$ if $X_{3p} \geq 2 X_{4p}$. (No hole is too close to a bend, so drilling is not required.)

The fourth mapping function describes how the design attributes correlate to the fourth process plan attribute, A_{4p}, the existence of an assembly operation. The design's process plan must include assembly ($A_{4p} = 1$) if the design has any anchors for screws ($X_{5p} = 1$).

$g_4(D_p) = X_{5p}$.

Thus, $g(D_p) = \{g_1(D_p), g_2(D_p), g_3(D_p), g_4(D_p)\}$.

Step 3

The plan-based design similarity measure $h(D_i, D_j)$ is the similarity between designs D_i and D_j.

$$h(D_i, D_j) = f(g(D_i), g(D_j))$$

Specifically, $h(D_i, D_j) = d_1 + d_2 + d_3 + d_4$. For each $k = 1, 2, 3, 4$, $d_k = 1$ if $g_k(D_i) = g_k(D_j)$ and 0 otherwise.

Thus we have defined a design similarity measure using the approach described in Section 3. For this measure, if $h(D_i, D_j) > h(D_i, D_k)$, then D_i is more similar to D_j than it is to D_k.

Similarity Analysis

Compare process plans P_1 and P_2 (Tables 2 and 3). $A_{11} = A_{12}$ because both process plans use the same brake. $A_{21} = A_{22}$ because both process plans include smooth corner arc welding at the same welding workcenter. $A_{31} = A_{32}$ because both process plans include drilling. $A_{41} = A_{42}$ because both process plans include assembly. Thus, for process plans P_1 and P_2, $f(P_1, P_2) = 4$. Likewise, $f(P_1, P_3) = 3$. $f(P_1, P_4) = 2$. $f(P_1, P_5) = 1$.

Compare designs D_1 and D_2 (Tables 4 and 5). $g_1(D_1) = g_1(D_2) = 2$ because both designs have bends that are greater than six feet. $g_2(D_1) = g_2(D_2) = 2$ because both designs have smooth corner arc welds. $g_3(D_1) = g_3(D_2) = 1$ because both designs have holes too close to a bend. $g_4(D_1) = g_4(D_2) = 1$ because both designs have anchors for screws. Thus, the similarity of designs D_1 and D_2, $h(D_1, D_2) = 4$.

Likewise, the similarity of designs D_1 and D_3, $h(D_1, D_3) = 3$. The similarity of designs D_1 and D_4, $h(D_1, D_4) = 2$. The similarity of designs D_1 and D_5, $h(D_1, D_5) = 1$.

The design similarity analysis yields the following conclusions:

1. The process plans corresponding to the designs D_1 and D_2 should have the same values for all the four process plan attributes because $h(D_1, D_2) = 4$. Thus the process plans will include the same optional operations.

2. The process plans corresponding to the designs D_1 and D_3 should have the same values for three process plan attributes. The process plans corresponding to the designs D_1 and D_4 should have the same values for two process plan attributes. The process plans corresponding to the designs D_1 and D_5 should have the same value for one process plan attribute.

Note that one can make these conclusions because the process plan similarity measure is so precise. Although the design similarity measure can exploit this precision, the design similarity measure cannot overcome an ambiguous process plan similarity measure.

GT classification

Compare these results to those that a PCA approach would yield.

One popular and practical GT code is the Multi-M GT coding and classification scheme (OIR, 1986). This scheme uses an 18 digit code to capture the most important design characteristics. For this example, we make the following assumptions. Because they apply to all five designs, the particular values will not change the analysis.

1. Each design’s function is a box.

2. Each design’s raw material is sheet stock, 0.2 inches thick.

3. Each design’s material chemistry is aluminum.

4. Each design’s production quantity is 100.

Table 6 briefly describes each position of the Multi-M GT code. From the information that Table 1 and the above assumptions provide, one can determine each design’s Multi-M GT code. Table 7 lists these codes.

Consider the design similarity measure that Offodile (1991) proposes:

$S_{ij} = (s_{ij1} + s_{ij2} + ... + s_{ijK})/(d_{ij1} + d_{ij2} + ... + d_{ijK})$.

$s_{ijk} = 1 - |x_{ik} - x_{jk}|/R_k$ for all $k = 1, ..., K$.

S_{ij} = similarity between design i and design j.

s_{ijk} = score between design i and design j on attribute k.

x_{ik} = design i’s value for attribute k.

x_{jk} = design j’s value for attribute k.

R_k = range of attribute k taken over the population space.

d_{ijk} = 1 if one can compare designs i and j on attribute k.

K = the total number of attributes.

Table 8 lists the resulting similarity between design D_1 and each of the other four designs. From these design similarity values one can draw the following conclusions:

1. Designs D_1 and D_5 are the most similar. The only identified difference is the length.

2. Designs D_3 and D_4 are less similar to design D_1.

3. Of the four designs under consideration, design D_2 is least similar to design D_1.

Now compare these conclusions to the conclusions that were drawn from the plan-based design similarity measure.

The GT code-based design similarity measure assigns a similarity value greater than 0.9 to each pair of designs. Yet, we know that the process plans for designs D_1 and D_5 have only one identical process plan attribute, and the process plans for designs D_1 and D_2 have four identical

process plan attributes. In fact, the GT code-based design similarity measure results contradict the process plan similarity measure results. Moreover, these values do not give any information about how similar the process plans are (are some, any, or all of the process plan attributes the same?).

This particular example clearly illustrates the inconsistent and imprecise nature of the GT code-based design similarity measure (as discussed before). One can conclude that, for design classification and variant process planning, the plan-based design similarity measure is a more relevant and precise measure than the GT code-based design similarity measure.

5. Summary and Conclusions

Identifying similar designs is an important step in generating a process plan. A design engineer can use a process plan for plan-based design evaluation. A process planner must generate the process plan before production can begin. In addition, a design engineer can use an existing, similar design's manufacturability to estimate a new design's manufacturability.

A variant process planning approach identifies similar designs. Specifically, it identifies the existing design (or product family) that is most similar to a new design. Thus, it must compare two designs and measure how much they resemble each other. A design similarity measure is a function that calculates this resemblance. However, existing design similarity measures, which do not explicity incorporate process plan similarity, are inconsistent and inappropriate measures for variant process planning.

This paper presents an approach for developing a new class of plan-based design similarity measures. The measure calculates the similarity of two designs. It requires a process plan similarity measure and mapping functions that describe the correlation of the design attributes and the process plan attributes. Thus, similar designs have similar process plans and similar manufacturability. The paper presents a three-step approach to create a plan-based design similarity measure that reflects local manufacturing characteristics and priorities.

The example clearly shows how such a measure is a more precise and consistent measure than a traditional GT code-based measure. The measure clearly identifies how two designs resemble each other, and the similarity measurement clearly corresponds to the process plan similarity.

For the future, we are considering a hybrid variant-generative process planning approach (Elinson *et al.*, 1997). The hybrid approach will decompose a design into independent sets of features, find similar feature sets in existing designs, retrieve the corresponding process plan segments, and combine them to construct a process plan for the new design. This approach's effectiveness depends upon good design similarity measures, and we hope to extend this idea to support the approach.

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Bibliography

Alting, Leo, and Hongchao Zhang, "Computer Aided Process Planning: The State-of-the-art Survey," *International Journal of Production Research*, Volume 27, Number 4, pp. 553-585, 1989.

Bakerjian, Ramon, editor, *Tool And Manufacturing Engineers Handbook, Volume VI: Design For Manufacturability*, Fourth edition, Society of Manufacturing Engineers, Dearborn, Michigan, 1992.

Bolz, Roger W. *Production Processes: Their Influence on Design*, The Penton Publishing Company, Cleveland, 1949.

Bralla, J.G., editor, *Handbook of Product Design for Manufacturing*, McGraw-Hill Book Company, New York, 1986.

Burbidge, J.L., *Production Flow Analysis for Planning Group Technology*, Clarendon Press, Oxford, 1989.

Candadai, A., J.W. Herrmann, I. Minis, "Applications of group technology in distributed manufacturing," *Journal of Intelligent Manufacturing*, Volume 7, pages 271-291, 1996.

Chang, Tien-Chien, and Richard A. Wysk, *An Introduction to Automated Process Planning*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1985.

Computer Aided Manufacturing Laboratory, *Part Family Classification and Coding*, Monograph Number 3, Brigham Young University, Provo, Utah, 1979.

Elinson, A., J.W. Herrmann, I. Minis, D. Nau, G. Singh, "Toward hybrid variant/generative process planning," Design for Manufacturing Symposium, ASME Design Engineering Technical Conference, Sacramento, California, September 14-17, 1997.

Elinson, A., D. S. Nau, and W. C. Regli, "Feature-based similarity assessment of solid models," Proceedings of the ACM Solid Modeling Conference, Atlanta, Georgia, May, 1997.

General Electric, *Manufacturing Producibility Handbook*, Manufacturing Services, Schenectady, NY, 1960.

Gupta, S.K., "Using manufacturing planning to generate manufacturability feedback," *Journal of Mechanical Design*, Volume 119, pages 73-80, 1997.

Halevi, Gideon, and Roland D. Weill, *Principles of Process Planning*, Chapman & Hall, New York, 1995.

Hayes, C.C., S. Desa, and P. K. Wright, "Using process planning knowledge to make design suggestions concurrently," in N. H. Chao and S. C. Y. Lu, editors, *Concurrent Product and Process Design*, ASME Winter Annual Meeting, pages 87-92, ASME, New York, 1989.

Hayes, C.C., and H. C. Sun, "Plan-based generation of design suggestions," in R. Gadh, editor, *Concurrent Product Design*, ASME Winter Annual Meeting, pages 59-69, Design Engineering Division, ASME, New York, 1994.

Hounshell, David A., *From the American system to mass production, 1800-1932*, The Johns Hopkins University Press, Baltimore, Maryland, 1984.)

Houtzeel, A., and B. Schilperoort, "A chain-structured part classification system (MICLASS) and group technology," Proceedings of the 13th Annual Meeting and Technical Conference, Cincinnati, Ohio, March 1976, pp. 383-400.

Hsu, Wynne, C. S. George Lee, and S. F. Su. "Feedback approach to design for assembly by evaluation of assembly plan," *Computer Aided Design*, Volume 25, Number 7, pages 395-410, July, 1993.

Ishii, Kosuke, "Modeling of concurrent engineering design," in *Concurrent Engineering: Automation*, *Tools and Techniques*, Andrew Kusiak, editor, pages 19-39, John Wiley & Sons, Inc., 1993.

Iyer, Shekhar, and Rakesh Nagi, "Identification and Ranking of Similar Parts in Agile Manufacturing," in *Concurrent Product Design*, edited by R. Gadh, pp. 87-96, ASME, New York, 1994.

Jakiela, M., and P. Papalambros, "Design and implementation of a prototype intelligent CAD system," *ASME Journal of Mechanisms, Transmission, and Automation in Design*, Volume 111, Number 2, page 252, June, 1989.

Kalyanapasupathy, V., Edward Y. Lin, and Ioannis Minis, "Group Technology Code Generation Over the Internet," 17th International ASME Computers in Engineering Conference, Sacramento, CA., September, 1997.

King, J.R., "Machine-Component Grouping in Production Flow Analysis: An Approach using Rank Ordering Clustering Algorithm," *International Journal of Production Research*, Volume 18, Number 3, pp. 213-37, 1980.

Kusiak, A., "The Generalized Group Technology Concept," *International Journal of Production Research*, Volume 25, Number 4, pp. 561-69, 1987.

Leung, H.C., E. L. Hines, and V. H. Raja, "The Application of Artificial Neural Networks in Computer Aided Process Planning," *Intelligent Engineering Systems through Artificial Neural Networks*, Volume 4, pp. 1091-6, 1994.

Minis, I., J.W. Herrmann, and G. Lam, "A generative approach for design evaluation and partner selection for agile manufacturing," T.R. 96-81, Institute for Systems Research, University of Maryland, College Park, Maryland, 1996.

Mitrofanov, S.P, *The Scientific Principles of Group Technology*, National Lending Library Translation, 1996.

Offodile, O.F., "Application of Similarity Coefficient Method to Parts Coding and Classification Analysis in Group Technology," *Journal of Manufacturing Systems*, Volume 10, Number 6, pp. 442-8, 1991.

OIR Multi-M Code Book and Conventions, Organization for Industrial Research, Waltham, Massachusetts, 1986.

Opitz, H., *A Classification to Describe Workpieces,* Pergamon Press, Oxford, 1970.

Pahl, G., and W. Beitz, *Engineering Design*, Design Council, London, 1984.

Radhakrishnan, Raj, Araya Amsalu, Mehran Kamran, and B.O. Nnaji, “Design rule checker for sheet metal components using medial axis transformation and geometric reasoning,” *Journal of Manufacturing Systems,* Volume 15, Number 3, pages 179-189, 1996.

Singh, Gurdip, *A Plan-Based Design Similarity Approach for Hybrid Process Planning*, M.S. Thesis 97-4, Institute for Systems Research, University of Maryland, College Park, 1997.

Snead, Charles S., *Foundation for Competitive Manufacturing*, Competitive Manufacturing Series, Van Nostrand Reinhold, 1989.

Sun, T.-L., C. -J. Su, R.J. Mayer, and R.A. Wysk, “Shape Similarity Assessment of Mechanical Parts Based on Solid Models,” *Proceedings of the 1995 Design Engineering Technical Conferences*, edited by O.M. Jadaan *et al.*, Volume 83, Number 2, pp. 953-962, ASME, New York, 1995.

Trucks, H. E., *Designing for Economic Production,* Society of Manufacturing Engineers, Dearborn, Michigan, 1987.

Wu, M.C., and S. R. Jen, “A Neural Network Approach to the Classification of 3D Prismatic Parts,” *International Journal of Advanced Manufacturing Technology*, Volume 11, pp. 325-335, 1996.

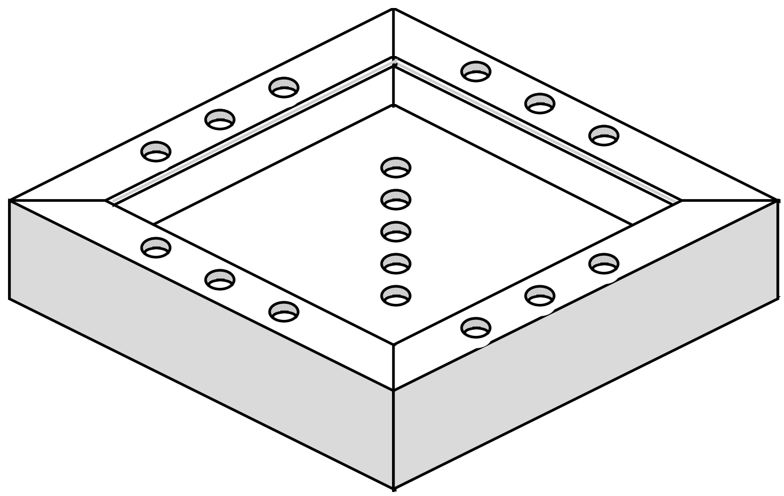

Figure 1. Sheet metal box.

	Length	Width	Welds	Holes	Hole-edge distance	Anchors?
D_1	84”	36”	Smooth-corner arc welds	Top 12, Bottom 5	0.2”	Yes
D_2	77”	7”	Smooth-corner arc welds	Top 12, Bottom 5	0.3”	Yes
D_3	84”	36”	Smooth-corner arc welds	None	0	Yes
D_4	36”	36”	Smooth-corner arc welds	Bottom 5	4”	Yes
D_5	70”	36”	Smooth-corner arc welds	Bottom 5	4”	No

Table 1. Critical design information.

Design	Plan	List of Operations
D_1	P_1	Operation 10 Punch blanks. Operation 20 Bend parts at Brake 10. Operation 30 Smooth corner arc welds at Welding 2. Operation 40 Grind slag at Welding 2. Operation 50 Drill holes. Operation 60 Insert anchors.
D_2	P_2	Operation 10 Punch blanks. Operation 20 Bend parts at Brake 10. Operation 30 Smooth corner arc welds at Welding 2. Operation 40 Grind slag at Welding 2. Operation 50 Drill holes. Operation 60 Insert anchors.
D_3	P_3	Operation 10 Punch blanks. Operation 20 Bend parts at Brake 10. Operation 30 Smooth corner arc welds at Welding 2. Operation 40 Grind slag at Welding 2. Operation 50 Insert anchors.
D_4	P_4	Operation 10 Punch blanks. Operation 20 Bend parts at Brake 6. Operation 30 Smooth corner arc welds at Welding 2. Operation 40 Grind slag at Welding 2. Operation 50 Insert anchors.
D_5	P_5	Operation 10 Punch blanks. Operation 20 Bend parts at Brake 6. Operation 30 Smooth corner arc welds at Welding 2. Operation 40 Grind slag at Welding 2.

Table 2. The process plans.

P_p	P_1	P_2	P_3	P_4	P_5
A_{1p}	2	2	2	1	1
A_{2p}	2	2	2	2	2
A_{3p}	1	1	0	0	0
A_{4p}	1	1	1	1	0

Table 3. The process plan attributes.

D_p	D_1	D_2	D_3	D_4	D_5
X_{1p}	84	77	84	36	70
X_{2p}	2	2	2	2	2
X_{3p}	0.2	0.3	0	18	18
X_{4p}	0.2	0.2	0.2	0.2	0.2
X_{5p}	1	1	1	1	0

Table 4. The design attributes.

D_p	D_1	D_2	D_3	D_4	D_5
$g_1(D_p)$	2	2	2	1	1
$g_2(D_p)$	2	2	2	2	2
$g_3(D_p)$	1	1	0	0	0
$g_4(D_p)$	1	1	1	1	0

Table 5. The mapping functions.

	Description
Position 1:	Main shape configuration e.g. a value of "6" implies that major deformations such as bending and/or deep drawing are present.
Position 2:	Perimeter e.g. a value of "9" implies a combination of cutout shapes.
Position 3:	Perpendicular hole configuration in layout plane e.g. a value of "2" describes line patterns
Position 4:	Machined secondary elements e.g. a value of "0" indicates no machined secondary elements.
Positions 5 & 6:	Function e.g. a value of "32" indicates that the function is a box.
Positions 7 & 8:	Dimension “A” e.g. a value of "89" indicates that the length is between 84.0 and 96.0 inches.
Positions 9 & 10:	Dimension “B” e.g. a value of "78" indicates that the width is between 36.0 and 38.0 inches.
Positions 11 & 12:	Material thickness e.g. a value of "08" indicates that thickness is between 0.187 and 0.250 inches.
Position 13:	Tolerances e.g. a value of "0" indicates no qualifying tolerances.
Positions 14 & 15:	Material chemistry e.g. a value of "60" indicates that the material is aluminum.
Position 16:	Raw material e.g. a value of "5" indicates that the raw material is sheet stock less than 0.25 inches thick.
Position 17:	Production quantity e.g. a value of "3" indicates that the production quantity is between 76 and 250 parts.
Position 18:	Bend complexity e.g. a value of "4" indicates that all bends are 90 degrees, all bends are open, and some bends are non-parallel.

Table 6. A brief description of each position of the Multi-M code

	1	**2**	**3**	**4**	**5, 6**	**7, 8**	**9, 10**	**11, 12**	**13**	**14, 15**	**16**	**17**	**18**
D_1	6	9	2	0	32	89	78	08	0	60	5	3	4
D_2	6	9	4	0	32	88	45	08	0	60	5	3	4
D_3	6	9	0	0	32	89	78	08	0	60	5	3	4
D_4	6	9	2	0	32	78	78	08	0	60	5	3	4
D_5	6	9	2	0	32	87	78	08	0	60	5	3	4

Table 7. Multi-M GT Codes

	Design similarity value
S_{12}	0.956
S_{13}	0.982
S_{14}	0.991
S_{15}	0.998

Table 8. The design similarity values using Offadile's measure.